Hadron Spectroscopy (theory): Diquarks, Tetraquarks, Pentaquarks and no quarks

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Abstract

States beyond those expected in the simple constituent quark model are now emerging. I focus on the scalar glueball and its mixing with states in the $q\bar{q}$ nonet, and also on correlations in Strong QCD that may form diquarks and seed $qq\bar{q}\bar{q}$ states. Some models of the pentaquark candidate $\Theta(1540)$ are critically discussed.

The meson landscape

This year we have seen several hadrons announced that do not fit easily with the simple valence picture of $q\bar{q}$ or qqq mesons and baryons. With hindsight one might wonder why it took so long. This simple picture exploits degrees of freedom that transform like the fields of L_{QCD} but are not identical to them. Two quarks attract one another in $\bar{\mathbf{3}}_\mathbf{c}$ with about the strength of $q\bar{q}$ coupled to colour singlet and so should play a significant role in in generating the colour degrees of freedom in Strong QCD. For light flavours there is even an old calculation[1] suggesting that the effective mass of the antisymmetric $[ud]$ pair, "scalar diquark", is comparable to that of a single $q \equiv u, d$. There is even some phenomenological support for this[2, 3]. If so it is energetically as easy to make colour singlets from $[qq][\bar{q}\bar{q}]$ as from $q\bar{q}$.

The low lying scalar mesons fit well with this idea[4, 5, 6]. This strong attraction of flavour antisymmetric scalar diquarks should even imply exotic combinations made from $[cs][\bar{u}\bar{d}]$, $[cd][\bar{u}\bar{s}]$ and $[cu][\bar{u}\bar{s}]$[7]. The idea that baryons may emerge naturally as excitations of a quasi-two centred system has been resurrected[3]. In turn this raises questions about other energetically favoured examples of such correlations. Two $[ud][ud]$ couple attractively to $\mathbf{3}_\mathbf{c}$ (probably forced into $L = 1$ by Bose symmetry[8]) and so need a further $\bar{\mathbf{3}}_\mathbf{c}$ to saturate. One way would be to add a third $[ud]$ (and another L=1 but even so the diquark mass cannot be too low if we are not to end up with a state more stable than the deuteron!) or a $\bar{q}$. If the latter is $\bar{s}$ we have a manifestly exotic strange baryon with the quantum numbers of the Θ, evidence for and against which has been extensively reviewed here[9].

But why stop at the diquark? A $[ud\bar{s}]$ combination also is strongly attractive and with different flavours does not suffer annihilation via gluons. This enables one to construct the Θ quantum numbers with a quasi-two centred system, $[ud\bar{s}][ud]$ with $L = 1$ needed to keep would be repulsive correlations apart[10]. Completing the simple quasi-two centred states are attractive combinations such as $[ud\bar{s}](\bar{s})$. The phenomenology of these includes flavour $\mathbf{10}$ and $\overline{\mathbf{10}}$ mesons, which might relate to exotic mesons with $J^{PC} = 1^{-+}$ at 1.4-1.6GeV[11], but the detailed similarities and differences with the $[qq][\bar{q}\bar{q}]$ remains to be investigated.

Most attention has focussed on the Θ and its implications for correlations as above. I shall not review this literature due to limitations of space and as it is well known, but I shall raise some questions that remain to be answered. While

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the above remarks may turn out to be critical in understanding the degrees of freedom for light flavours, the heavy flavours are better understood. Their phenomenology gives hints as to how to begin unravelling the code of the light flavoured sector.

So I shall begin with the $b\bar{b}$ and $c\bar{c}$ traditional realm where the non relativistic model works well, at least as far as the S and P wave combinations are concerned. In particular note the scalar mesons are canonical: they are in the right place, the E1 radiative transitions from 2^3S_1 and their decays to 1^3S_1 appear to be in accord with theory[12]. The $^1P_1$ charmonium state has been reported[13].

A novel entree to light hadrons is emerging with the decays of these χ states[14]. $\chi_0 \to \pi^+\pi^-\pi^+\pi^-$ shows $f_0(980)f_0(980)$ pair production at a strength similar to that of $K\bar{K}$; this is a surprise if the $f_0(980)$ is purely a $qq\bar{q}\bar{q}$ state and suggests that in **production** by hard gluons the "simplest" $q\bar{q}$ or gg configuration dominates the dynamics (I shall contrast this with its appearance in $\phi \to \gamma f_0(980)$ later). In the present data $\chi_0 \to \pi + (3\pi)$ should be studied to see if the $\pi(1800)$ is prominent: this is a potential candidate for a gluonic excitation of the π and is degenerate with the D. This is an example of how light hadron dynamics needs to be understood as it can affect D decays: the Cabibbo suppressed decays of the D can be affected by mixing with this $\pi(1800)$[15]. We now await data on $\chi_1 \to \pi + X$; this is intriguing because in S-wave $X \equiv 1^{-+}$, predicted to be the lightest exotic gluonic hybrid channel. Production by the short distance gluons in χ decays is thus eagerly awaited.

What do we expect to find in the spectroscopy of light flavours? The $Q\bar{Q}$ pattern of S P D states that was apparent for heavy quarkonium seems to survive for light flavours, though there is no fundamental a priori reason why we should have expected this. There is however a clear indication of where it does not work. In the P-wave states the $2^+, 1^+$ nonets, each containing two isoscalars representing the $s\bar{s}$ and $n\bar{n}$ flavour combinations, are clearly seen even though these states are now above threshold for decays into mesons. The rule seems to be that the spectroscopy seeded by a short range $q\bar{q}$ remains visible so long as there are no open **S-wave** hadron channels, which obscure the underlying short range structure. This is particularly obvious in the 0^+ sector. Above 1GeV we find three I=0 (1370;1500;1710) - or even a fourth $f_0(1790)$[9] - in place of two, and below 1 GeV there are certainly two further states $f_0(980)$ and $a_0(980)$ and attractive channels hinting at a full nonet including a further I=0 $\sigma(600)$. Intriguingly, this proliferation is in accord with simple ideas from QCD.

Above 1 GeV Lattice QCD predicts a scalar glueball, mass ~ 1.6 GeV[16, 17], which mixes[18] with the isoscalar $q\bar{q}$ in its vicinity. In the limit of large mixing, the flavour eigenstates tend towards **1+G**, **8**, **1-G**[17]. Fits to the pseudoscalar meson decays from WA102 and LEAR give independent support to such relative phases[19]

$$\begin{pmatrix} Meson & G & s\bar{s} & n\bar{n} \\ 1710: & 0.4 & 0.9 & 0.1 \\ 1500: & -0.6 & 0.3 & -0.7 \\ 1370: & -0.7 & 0.15 & 0.7 \end{pmatrix}$$

The fact that mass mixing and also meson decays are consistent with this

set of relative phases is interesting. The numerical values should not be taken seriously; the errors on them are probably considerable, but the relative phases and separation of "large, medium, small" is probably reliable.

These independent analyses give a consistent interpretation of the glueball-$q\bar{q}$ mixing in the scalar channel. The challenge is how to test this? BES and CLEO-c will soon provide over a billion ψ decays giving over a thousand events per channel in the radiative decays $0^{++} \to \gamma(\rho;\omega;\phi)$. The ideal flavour mixing of the vector mesons will thus "weigh" the flavour contents of any C=+ meson produced in $\psi \to \gamma R$.

Some preliminary hints that there is such mixing come from the anomalous pattern of meson states M_2in $\psi \to \omega/\phi + M_2$[9]. For an ideal flavour combination, such as $\phi = s\bar{s}$, then the folklore is that M_2 will be produced via its $s\bar{s}$ content as this leads to a flavour connected diagram. Similarly the ω selects out $n\bar{n}$ for the M_2. The test of this hypothesis has been when $M_2 \equiv 2^{++}$; this nonet consists of ideal states $a_2(1320); f_2(1270) \equiv n\bar{n}; f_2(1525) \equiv s\bar{s}$ and therefore is rather clean and confirms the dominance of the "hairpin" diagram. However, the case $M_2 = 0^{++}$ has no simple solution. Indeed, some channels which ought to have been dominant appear even to be absent. For example: $f_0(1370)$ has strong affinity for $\pi\pi$ and hence $n\bar{n}$ in its wavefunction yet is not seen in $\psi \to \omega\pi\pi$. This being anomalous does not require one to suppose that $f_0(1370)$ is $n\bar{n}$ alone; multiquark components containing non-strange flavours ought to be enough to highlight the paradox. One explanation could be that some other contribution leads to destructive interference. The G component in the $f_0(1370)$ wavefunction is a natural candidate for this and it has even been predicted[20] that the strength of $b(\psi \to \phi G) \sim 10^{-3}$; if this also applies to $b(\psi \to \omega G) \sim 10^{-3}$ then the destructive interference becomes plausible. The test will be to see if the relative phases of G and flavored components are in line with the observed pattern of suppressed and observed decays $\psi \to \omega/\phi f_0$.

Below 1GeV the dynamics are controlled by the strong attractive QCD forces between colour-spin symmetric qq (or $\bar{q}\bar{q}$) pairs, for example $S = 0\ \bar{\mathbf{3}}_F$. In flavour this equates to attraction in $\bar{\mathbf{3}}_F$. This leads to a nonet of low lying scalars[5]. Recent data from KLOE on $\phi \to \gamma f_0/a_0(980)$ support this picture[6, 21] though the role of $K\bar{K}$ threshold in disturbing the short disance diquark clustering dynamics from the looser molecular[22] remains to be determined[6, 23]. The dominant production is via the $\phi \to K\bar{K} \to K\bar{K}\gamma \to 0^{++}\gamma$ loop: this produces the f_0/a_0 via their long range wavefunction and does not teach much about the short range QCD structure.

These tentative ideas on diquark or molecular clustering may now be receiving support from the heavy flavour sectors.

The X(3872): anomalous charmonium

B decays have turned out to be a novel and rich source of charmonium. Among these is a narrow state $X(3872) \to \psi\pi\pi$. Immediately above $D\bar{D}$ threshold states can remain narrow if they are forbidden to decay into $D\bar{D}$. Examples are $2^{-\pm}, 3^{--}$ and radially excited 1^{++} within the $c\bar{c}$; also, hybrid charmonium or DD^* molecular state.

However, each of these has problems[24]. Compared to predictions in charmonium potential models: 2^{--} and 3^{--} have the wrong mass and the experimental $\Gamma(\gamma 1^+)$ is too small; for 2^{-+} the $b(\psi\pi\pi)$ is expected to be small, in contrast to its visibility there; the radial 1^{++} is expected to have a larger $\Gamma(\gamma\psi)$ than seen; the 1^{+-} has a different cosθ distribution. Either standard $c\bar{c}$ theory

is wrong or the $X(3872)$ is not a simple charmonium state.

The latter is suspected to be the case, in part driven by the remarkable coincidence between its mass and that of the threshold for D^0D^{0*} which agree to better than one part in 10,000. Refs[25] suggest that it is a molecular or tetraquark bound state of these mesons in S-wave; thus 1^{++}. A particular model realisation is due to Swanson[26].

Observation[27] of the $\psi\omega$ decay supports $C=+$ and the hint that the decay to $\psi\pi\pi$ has the $\pi\pi\equiv\rho$ and not σ support the isospin violation that the D^0D^{0*} constitution would imply. Further tests include verifying that there is no $\psi\pi^0\pi^0$: forbidden for the ρ but allowed for σ. Also the hadronic decays into e.g. $K\bar{K}\pi$ will be dominated by neutral $K^0\bar{K}^0\pi$ relative to $K^+K^-\pi$. .

The $DD^*, \psi\omega; \psi\rho$ are all effectively mass degenerate. So a mixing via quark exchange $D^0D^{0*}\to\psi u\bar{u}$ is driven by the energy coincidence, which is probably more generally true than the details of any particular model. The $u\bar{u}$ maps equally onto ρ,ω and so one expects $\psi\omega\sim\psi\rho$, any deviations from equality being a pointer to dynamical effects. Decays are driven by the meson components of the wavefunction while the production will be by the easiest route; thus seeding by the short range $c\bar{c}$ component will cause the X to be produced like conventional charmonium states.

There may be analogues of this dynamics in the $\psi\to(K\Lambda)\bar{p}$ where the $K\Lambda$ appear to have S_{11} baryon quantum numbers. This is another example of the S-wave hadron channels overriding the P-wave quark structure (in this case qqq): quark exchange links the $N\eta\to K\Lambda$. The $\psi\to\gamma p\bar{p}$ also may be showing S-wave enhancements; whether these are evidence of a bound state or above threshold S-wave attractions remains to be determined, though comparison with the LEAR data on $p\bar{p}$ annihilation just above threshold supports the bound state interpretation [9].

Strange strange-charmed states: 2317,2460, 2635 MeV

The $0^+,1^+$ at 2317 and 2460MeV are lighter than the quark model had predicted, even though it had been successful hitherto in this sector. One interpretation is that this is evidence for a chiral symmetry where the mass gap of $0^-:1^-$ equates with $0^+:1^+$[28]. Why does this show up in $c\bar{s}$ where no u,d chiral-friendly flavours are involved? And the axial ought to be the $j=1/2$ member whereas the physical states are mixtures of $j=1/2,3/2$. Thus unless one can argue that the 2460 is the $j=1/2$ member, the identity in the mass gaps appears a tantalising coincidence. The chiral relation may be applicable in the $M_Q\to\infty$ limit when u,d accompany the heavy quark; its application in the finite mass case with s is less clear.

The coincidence of the masses lying just below the DK and D^*K thresholds has led to suggestions that their masses are lowered from the naive $c\bar{s}$ by a mechanism similar to that responsible for lowering the $f_0(980)$ and $a_0(980)$ to the vicinity of the $K\bar{K}$ threshold. The challenge now is to distinguish beetween $c\bar{s}$ and molecule interpretations. One suggestion is the radiative transition $1^+\to 0^+\gamma$. In the molecule interpretation this is driven by $D^*\to D\gamma$ which is known. In the $c\bar{s}$ this branching ratio is predicted to be 1.2×10^{-3}[29].

$D_s(2632)$ has anomalous branching ratios favouring $D_s\eta$ over DK. Attempts to accomodate these within the $c\bar{s}$ picture (as a radial excitation of the 1^-) exploiting nodes in the radial wavefunction are unable to do so without choosing unrealistic values of established parameters. Suggestions that it is a tetraquark ($cu\bar{s}\bar{u}$) which feeds $D_s\eta$ and not DK run into problems as they also imply $D_s\pi^0$

decays. These would feed $D_s\gamma\gamma$ but there is no sign of an enhancement at 2632 in these data. Ref.[30] concludes that either our understanding of hadron decays is wrong or this state is an artefact. Its non observation in other experiments adds weight to this interpretation.

Some reflections on pentaquarks

If narrow width pentaquarks exist with positive parity, powerful correlations must arise in Strong QCD. In QCD attractions are predicted between distinct flavoured pairs in net spin zero, which is the starting point of two particular models[8, 10]. It has not been demonstrated how scalar diquarks form with ultra-light masses as required to accomodate a 1540 MeV state; their stability is an open question; their effective boson nature and consistency with hadron spectroscopy also are not well understood. But first we need to establish whether this state is real. I shall now review various features.

Mass

The original prediction[31] assumed that the 1710 N^* is in the $\bar{10}$ and used this to set the scale of mass. However $\gamma p \to p^*(\bar{10})$ is forbidden by U-spin which argues against this[12]. The mass gap of 180MeV per unit of strangeness is also suspect in a quark model interpretation as it leads to a 540MeV spread across the $\Theta - \Xi$ multiplet even though there is only one extra strange mass in going from $(udud\bar{s})$ to $(usus\bar{d})$ and so a much smaller gap would be anticipated[8]. Beware also naive application of Gell Mann Okubo mass formulae which do not distinguish between $|S|$ and S as one goes from $\Theta(S = +1)$ to $\Xi(S = -2)$.

If the Θ should prove to be real, then no simple mapping from chiral soliton onto a pentaquark description seems feasible. The relation between these is more profound. Nonetheless a narrow state of mass ~1540MeV has been claimed. But when one compares the masses reported in K^+n versus K^0p there appears to be a tantalising trend towards a difference[32]. Is this a hint of an explanation (see later) or that we are being fooled by poor statistics?

No models successfully predict the mass; in all cases it is fitted relative to some other assumed measure. The original chiral soliton normalised to the 1710, as we already discussed. Ref.[8] assume that the Roper 1440 is the $udud\bar{d}$ (but this state is partnered by $\Delta(1660)$ which along with its electromagnetic and other properties, is in accord with it being a radial qqq excitation of the nucleon). Ref[10] noted the kinematic similarity between reduced masses in their diquark-triquark model and the $c\bar{s}$ system. They adopted a 200MeV orbital excitation energy from the $1^- - 0^+(2317)$ mass gap to realise a 1540MeV mass for the Θ. However, if one makes a spin averaged mass for the $L = 0, 1$ levels, notwithstanding the questions about the low mass of the 2317, one gets nearer to a 450 -480MeV energy gap and hence a $\Theta \sim 1800$ MeV. In summary, all models appear to normalise to some feature and do not naturally explain the low mass of an orbitally excited pentaquark.

Width

The chiral soliton model Lagrangian contains three terms with arbitrary strengths, A, B, C. Linear combinations of these can be related to the observable transition $\Delta N\pi$ and the F/D ratio for the $NN\pi$ vertex. The ΘNK vertex is then given by $g(\bar{10}) = 1 - B - C$. We thus have one unknown $g(\Theta NK)$ described by another unknown, C. Ref[33] shows the coupling is relatively insensitive to F/D and that it is C that controls $g(\Theta NK)$. In the non relativistic quark model it is argued[31, 33] that $F/D = 2/3$ and the absence of $s\bar{s}$ in the nucleon lead to $B = 1/5; C = 4/5$. This has the remarkable implication that $g(\Theta NK) = 0$.

If the Θ phenomenon survives then a deeper understanding of this result and its implications would be welcome. It would also raise the challenge of how the Θ is strongly produced.

Phenomenologically $\Gamma(\Lambda(1520) \to KN) \sim 7$MeV has been suggesttted as a measure for narrow widths. However this is D-wave and phase space limited: the P-wave $\Lambda(1660)$ width is ~ 100MeV. Furthermore these decays require creatioon of a $q\bar{q}$; for the pentaquark one has $qqqqq\bar{q}$ and the challenge is to stop its decay. There are no indications in conventional spectroscopy underpinning a narrow width of ~ 1MeV for Θ.

Colour spin and flavour mismatches between Θ and NK wavefunctions have been proposed to suppress the natural width by large factors[34]. However it is easy to override these: soft gluon exchange defeats the colour; spin flip costs little and flavour rearrangement can occur. Further there is colour singlet $q\bar{q}$ in relative S-wave within the correlated models of JW and KL[35] and their dissociation into NK seems hard to prevent.

Ref[36] suggested that overlaps of spatial wavefunctions between pentaquark and nucleon may lead to a suppression. However it has not been demonstrated that such is generated dynamically. Dudek has shown[35] that such an effect can arise but this involves taking a non relativistic picture rather literally. It is also unclear how a colour $\bar{3}$ diquark is attracted into a tighter (smaller?) configuration than a colour singlet meson.

We almost have a paradox here. The small width implies a feeble coupling to KN, yet something must couple to Θ strongly to give a normal hadronic production rate[9]. This is an enigma which we must confront.

Production

We have heard several experimental limits on the hadroproduction of the Θ. Some are not yet restrictive,e.g. the limit in $\psi \to \Theta\bar{\Theta}$ which is phase space limited or that in ψ' decay where one can claim that there is a big price to pay for creating ten q and $\bar{q}$. So it is possible to wriggle. However on balance the limits in high statistics hadroproduction appear impressive. The onus is on supporters to explain them away or find a loophole.

An example of such a loophole suggested here[37] asks why signals are in photoproduction but not in hadroproduction. The photon contains $s\bar{s}$ and so may be able to feed the $\bar{s}$ needed to make $\Theta(udud\bar{s})$ in a way not so readily accessible in hadroproduction. Further appeal is made to a CLAS observation that suggests that a narrow N^* at ~ 2.4GeV may be the source of $\Theta + K$. While such a dynamics can be tested by searching for other decay modes, forced by SU(3)[37], there remain problems. CLAS see this (statistically insignificant) N^* in π exchange and so the photon does not appear to be essential: why is this object (and its progeny, the Θ) not also made in hadroprodcution if it is made by πN? Second; while a 2.4 GeV N^* may be produced in the 3-5 GeV CLAS experiment, it is kinematically inaccessible in the original SpRING8 experiment and in the earlier CLAS γd. So the source of Θ in this latter pair would still remain to be explained.

Ref[38] have noted that the relative photoproduction strengths of Θ and the related Σ_5^+ should be similar even though the scale of each individually is highly model dependent. As either of these can decay into $K_s p$, the absence of any Σ_5^+ signal (even after mixing with known Σ^*) accompanying the claimed Θ in the HERMES data for example raises questions.

Photoproduction has also been suggested as a source of kinematic peaks that

fake a Θ[39]. $\gamma N \to a_2/\rho_3 N$ followed by the $K\bar{K}$ decays of these mesons in D/F waves give a forward-backward peaking in the c.m. along the direction of the recoil nucleon and a spurious KN peak. At first sight the experimental absence of such peaks in K^-n supports for the reality of the peak in K^+n, but it is not necessarily so simple. Charge exchange and D/F interference can introduce a charge asymmetry and it is claimed to be possible to choose phases such that a narrow peak can arise in K^+n (after feeding through Monte Carlo) whereas broad structure would arise in K^-n. It has been suggested in the discussion sessions here that the different Q-values could cause a mass shift in the kinematic peak in K^+n versus K^0p, in accord with the trend of the data[40]. Whether this kinematic effect is responsible may be settled when higher statistics data and significant Dalitz plots become available.

Conclusion

Precision and variety in experiments are taking us beyond the 40 year old simple $q\bar{q}$ quark model of mesons. The role of strong glue in QCD is tantalising: $\psi \to \gamma\gamma V$ is a novel opportunity that can test the current interpretation of the mixing between scalar glueball and $q\bar{q}$ above 1GeV. Evidence for exotic hybrid mesons is emerging; $\chi_1 \to \pi X$ in S-wave immediately accesses the exotic $X = 1^{-+}$ channel. The analogous $\chi_0 \to \pi X$ probes $X = 0^{-+}$ where production of $\pi(1800)$ (a potential hybrid partner of the pion, and interesting due to its mass degeneracy with the charmed D) may be studied.

Multiquark molecules are appearing. I suggest that $X(3872)$ is 1^{++}; the $D_s(2317/2460)$ are $0^+, 1^+$ shifted to below DK/D^*K thresholds by dynamics analogous to those that pull the $f_0(980)$ and $a_0(980)$ to below the $K\bar{K}$ threshold. Ways of testing this need to be clarifyied. I suggest that the $D_s(2632)$ is an artefact: data can easily prove me wrong.

The Θ, and the question of narrow width pentaquark(s), is rightly at the centre of attention. Either the Θ is some artefact (if so, what?) or, if real, the behaviour of Strong QCD is profound and our current model attempts will turn out to be mere tinkering.

For future historians the vote taken at this conference from around 1000 physicists was $\sim 60\%$ believe the evidence remains inconclusive; $\sim 40\%$ believe that the Θ is not a resonance and in the dark of the hall only a handful were convinced that a genuine narrow resonance has been found. A vote taken a year ago at Hadron03 scored $\sim 50\%$, 25% and 25% respectively. Time will tell.

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